

# An Examination of Tropical Cyclone Position, Intensity, and Intensity Life Cycle within Atmospheric Reanalysis Datasets

### BENJAMIN A. SCHENKEL AND ROBERT E. HART

Department of Earth, Ocean, and Atmospheric Science, The Florida State University, Tallahassee, Florida

(Manuscript received 16 November 2010, in final form 29 August 2011)

#### ABSTRACT

The following study examines the position and intensity differences of tropical cyclones (TCs) among the Best-Track and five atmospheric reanalysis datasets to evaluate the degree to which reanalyses are appropriate for studying TCs. While significant differences are found in both reanalysis TC intensity and position, the representation of TC intensity within reanalyses is found to be most problematic owing to its underestimation beyond what can be attributed solely to the coarse grid resolution. Moreover, the mean life cycle of normalized TC intensity within reanalyses reveals an underestimation of both prepeak intensification rates as well as a delay in peak intensity relative to the Best-Track. These discrepancies between Best-Track and reanalysis TC intensity and position can further be described through correlations with such parameters as Best-Track TC age, Best-Track TC intensity, Best-Track TC location, and the extended Best-Track TC size. Specifically, TC position differences within the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), ECMWF Interim Re-Analysis (ERA-I), and Modern Era Retrospective-Analysis for Research and Applications (MERRA) exhibit statistically significant correlations  $(0.27 \le R \le 0.38)$  with the proximity of TCs to observation dense areas in the North Atlantic (NATL) and western North Pacific (WPAC). Reanalysis TC intensity is found to be most strongly correlated with Best-Track TC size  $(0.53 \le R \le 0.70$  for maximum 10-m wind speed;  $-0.71 \le R \le -0.53$  for minimum mean sea level pressure) while exhibiting smaller, yet significant, correlations with Best-Track TC age, Best-Track TC intensity, and Best-Track TC latitude. Of the three basins examined, the eastern North Pacific (EPAC) has the largest reanalysis TC position differences and weakest intensities possibly due to a relative dearth of observations, the strong nearby terrain gradient, and the movement of TCs away from the most observation dense portion of the basin over time. The smaller mean Best-Track size and shorter mean lifespan of Best-Track EPAC TCs may also yield weaker reanalysis TC intensities. Of the five reanalyses, the smaller position differences and stronger intensities found in the Climate Forecast System Reanalysis (CFSR) and Japanese 25-year Reanalysis (JRA-25) are attributed to the use of vortex relocation and TC wind profile retrievals, respectively. The discrepancies in TC position between the Best-Track and reanalyses combined with the muted magnitude of TC intensity and its partially nonphysical life cycle within reanalyses suggests that caution should be exercised when utilizing these datasets for studies that rely either on TC intensity (raw or normalized) or track. Finally, several cases of nonphysical TC structure also argue that further work is needed to improve TC representation while implying that studies focusing solely on TC intensity and track do not necessarily extend to other aspects of TC representation.

### 1. Introduction

The emergence of atmospheric reanalysis datasets has provided tools of great utility for studying climatescale processes that include the impacts of larger-scale mechanisms on tropical cyclones (TCs; e.g., Maloney and Hartmann 2000a,b) and the potential feedbacks of TCs upon the larger scales (e.g., Hart et al. 2007; Hart 2010). Reanalyses provide a unique opportunity for studying TCs by providing complete spatial and temporal data coverage over long time periods that are only affected by changes in the observing system (Thorne and Vose 2010). Previous climate-scale studies of TCs utilizing reanalyses have included Hart et al. (2007) who used the 40-year European Centre for Medium-Range

*Corresponding author address:* Benjamin A. Schenkel, Department of Earth, Ocean, and Atmospheric Science, The Florida State University, Tallahassee, FL 32306. E-mail: benschenkel@gmail.com

DOI: 10.1175/2011JCLI4208.1

Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) to quantify the environmental "memory" of TC passage. The ERA-40 was also used by Sriver and Huber (2006) to calculate TC power dissipation (Emanuel 2005) to argue that increases in sea surface temperatures (SSTs) were driving changes in power dissipation. In a separate study, data from the ERA-40 were used to estimate the average global oceanic heat transport attributable to TCs (Sriver and Huber 2007). Reanalyses have also been used to correlate TC activity with the strength of the meridional temperature flux during the following winter to indirectly determine whether TCs are significant contributors to atmospheric poleward heat transport (Hart 2010). Truchelut and Hart (2011) utilized both reanalysis data and in situ observations to identify candidate warm-core cyclones for consideration for addition to the National Hurricane Center (NHC) Best-Track dataset (Jarvinen et al. 1984; Neumann et al. 1993) as TCs. In light of the increased usage of reanalyses for studying TCs, guidance is necessary to determine when the degree of TC representation within reanalyses is sufficiently robust for such studies and to quantify the strength of any nonphysical relationships for TC position, intensity, and the life cycle of intensity.

The importance of properly representing TCs may have implications that extend to accurately depicting their larger-scale environment within reanalyses. While the aggregate impact of TCs upon the coupled climate has remained unquantified, localized effects of TC passage include SST anomalies lasting up to two months after TC passage (Schenkel and Hart 2010) and moisture and temperature anomalies that exist for as long as several weeks (Hart et al. 2007). Other studies have hypothesized that anomalously strong trade winds in global climate models are due to the muted structure of TCs (Trenberth and Fasullo 2007). Previous work has also suggested that recurving TCs may alter the midlatitude Rossby wave pattern for weeks following TC passage (McTaggart-Cowan et al. 2007; Riemer et al. 2008; Harr and Dea 2009; Cordeira 2010). McTaggart-Cowan et al. (2007) also argued that recurving TCs can both transfer substantial amounts of heat from low to high latitudes and aid in the formation of new TCs. Furthermore, recent work has also indicated that aggregate TC power dissipation is strongly correlated with the strength of meridional heat transport during the following winter possibly indicating that TCs play a relevant role in atmospheric poleward heat transport (Hart 2010). TCs are also known to contribute substantial proportions of rainfall within certain basins (Jiang and Zipser 2010). Given the influence of TCs on regional and potentially global scales, the question is raised as to whether the quality of the representation of the general circulation within reanalyses suffers significantly, particularly on shorter time scales, due to the muted structure of TCs that primarily results from the coarse resolution of reanalyses (e.g., Walsh et al. 2007).

While several studies have utilized reanalyses for studying TCs, relatively few have quantitatively evaluated TC representation within these datasets. Typically, examination of the ability of reanalyses to represent TCs has been limited to the frequency of TC detection using automated tracking algorithms. The parameters chosen for a given algorithm vary among each reanalysis with thresholds subjectively chosen to yield detection rates on the order of 75% or greater for Best-Track TCs. The only attempt at comparing detection rates using a uniform algorithm was performed by Onogi et al. (2007) who examined detection frequencies for the ERA-40 and the Japan Meteorological Agency (JMA) Japanese 25-year Re-Analysis (JRA-25; Onogi et al. 2007). While over 80% of TCs globally were trackable within the JRA-25, the same algorithm applied to the ERA-40 yielded global detection rates below 60% (Onogi et al. 2007). The lower detection frequencies in the ERA-40 were attributed to the weaker intensity of TCs within this dataset, which failed to meet the detection thresholds (Hatsushika et al. 2006). These results seemingly contrast with those given by Uppala et al. (2004) who show global detection rates of over 90% for the same period of study within the ERA-40. Thus, while the choice of an automated tracking algorithm is seemingly objective, the thresholds used to identify TCs within them are less so.

Despite the recent proliferation of reanalyses for use in studying TCs, studies by Hatsushika et al. (2006), Onogi et al. (2007), and Manning and Hart (2007) remain the only attempts at evaluating reanalysis TC intensity or structure. Hatsushika et al. (2006) utilized stormrelative composited temperature anomalies to quantify the reanalysis TC warm core for comparison with previous observational work. The maximum composited temperature anomaly of 6°C in the JRA-25 (Hatsushika et al. 2006) was found to be several degrees lower than the observations found in TC Hilda (1964; Hawkins and Rubsam 1968) owing to the coarse spatial resolution of the reanalysis and the compositing process (Hatsushika et al. 2006). Onogi et al. (2007) showed that both the ERA-40 and JRA-25 had a more robust representation of the temperature anomalies associated with the TC warm core within the western North Pacific (WPAC) relative to the eastern North Pacific (EPAC; Onogi et al. 2007). These differences were attributed to the relative sparseness of observations in the EPAC (Hatsushika et al. 2006). Moreover, the peak magnitude of the upper-level temperature anomaly

TABLE 1. Salient characteristics of the CFSR, ERA-40, ERA-I, JRA-25, and MERRA for this study. Included in the chart is the native resolution of each reanalysis (Native resolution), the resolution at which the data is available at in isobaric coordinates in this study (Postprocessed resolution), the period (YYYY.M) over which each reanalysis is available over at the time of this research (Reanalysis period), the type of data assimilation method used (DA type), and whether TCs received any supplemental treatment (TC treatment). For the number denoting the resolution, *T* refers to the mean wave truncation number, and *L* refers to the number of vertical levels. The asterisk denotes that the values given represent the approximate horizontal resolution for the available data due to the use of a reduced Gaussian grid.

Reanalysis	Native resolution	Postprocessed resolution	Reanalysis period	DA type	TC treatment
CFSR	T382 L64	$0.50^\circ  imes 0.50^\circ$ L37	1979.0-present	3DVAR	Vortex relocation
ERA-40	T159 L60	$1.13^{\circ} \times 1.13^{\circ} \text{ L16*}$	1957.9-2002.8	3DVAR	None
ERA-I	T255 L60	$0.70^\circ  imes 0.70^\circ$ L37*	1989.0-present	4DVAR	None
JRA-25	T106 L40	$1.25^{\circ} \times 1.25^{\circ}$ L23	1979.0-present	3DVAR	TC wind profile retrieval
MERRA	$0.50^\circ  imes 0.67^\circ$ L72	$0.50^\circ  imes 0.67^\circ$ L42	1979.0-present	3DVAR	None

within the ERA-40 was also up to 1°C smaller than in the JRA-25 (Onogi et al. 2007).

A more rigorous attempt at addressing reanalysis TC representation was undertaken by Manning and Hart (2007) who examined whether trends in the depiction of North Atlantic (NATL) TCs within the ERA-40 were significantly different from those in the Best-Track. Manning and Hart (2007) determined that nonphysical, statistically significant temporal trends likely existed in reanalysis TC intensity and structure due to improvements in the density of the observing system. Specifically, TCs occurring in the early period (1957–71) within the ERA-40 were shown to not have statistically significant different intensities and structures from those TCs that were one to two Saffir–Simpson categories weaker in the Best-Track during the latter period (1988–2001; Manning and Hart 2007).

While Manning and Hart (2007) provided the initial attempt at examining TC intensity and structure in reanalyses, there has yet to be a comprehensive intercomparison of both TC position and intensity in multiple basins within the current generation of reanalysis datasets using a consistent tracking methodology. The following study seeks to quantify the depiction of TC position, intensity, and the life cycle of intensity among five reanalysis datasets to determine their suitability for examining TCs. The remainder of this paper will be divided into three parts. Section 2 will detail the data and methodology used in this study. Section 3 will discuss the variability of TC position and intensity within and among reanalyses. Section 4 will provide a summary of the results and some concluding thoughts.

#### 2. Methodology

#### a. Data

For this study, TC position difference and intensity are evaluated within five reanalysis datasets. Position difference is defined here as the difference between the Best-Track and reanalysis TC position. The reanalyses chosen for this study include the ERA-40, the ECMWF Interim Re-Analysis (ERA-I; Dee et al. 2011), the JRA-25, the National Aeronautics and Space Administration (NASA) Modern Era Retrospective-Analysis for Research and Applications (MERRA; Rienecker et al. 2011), and the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR; Saha et al. 2010). Salient details of each reanalysis for this study are found in Table 1.

Three of the five reanalyses have unique properties intended to improve TC representation. The first distinctive feature is the use of four-dimensional variational data assimilation (4DVAR) in the ERA-I which contrasts with the use of three-dimensional variational data assimilation (3DVAR) within the four remaining reanalyses. In addition to handling asynoptic data more accurately, 4DVAR allows for the influence of an observation to be more strongly controlled by model dynamics (Thépaut et al. 1996). As a result, 4DVAR should yield improved performance in observation deficient regions in which TCs are typically found (Thépaut 2006; Whitaker et al. 2009; Dee et al. 2011). A second unique property is the use of TC wind profile retrievals within the JRA-25 for all Best-Track TCs with a maximum 10-m wind speed (VMAX<sub>10m</sub>) greater than or equal to 34 kt. TC wind profile retrievals use Best-Track data to generate synthetic dropwindsondes that approximate the TC wind profile at the Best-Track location (Hatsushika et al. 2006) yielding reduced position differences and stronger reanalysis TC intensities (Hatsushika et al. 2006; Onogi et al. 2007). A third distinctive feature is the use of vortex relocation in the CFSR. Vortex relocation involves either moving the vortex from its position in the first-guess field to its Best-Track location or inserting a synthetic vortex into the first-guess profile if the initial vortex is absent or too weak for the given spatial resolution. In addition to correcting TC position, improvements in reanalysis TC intensity will likely result from the TC being moved into the correct environment. Furthermore, observations within the TC are more likely

to be accepted during data assimilation due to the TC being properly located within the first-guess field (Liu et al. 2000).

Several other improvements with more secondary impacts on TC representation are found in the reanalyses. Among these is the use of raw satellite radiances in the CFSR, ERA-I, and MERRA as opposed to onedimensional variational data assimilation (1DVAR) retrievals since the latter of the two assimilation methods is more difficult to establish observation errors for (Andersson et al. 2005). Another improvement is the use of variational bias correction of satellite radiances in the CFSR, ERA-I, and MERRA. Instead of making manual changes to radiances, which can be error prone (Dee and Uppala 2009), variational bias correction automatically adjusts radiances to be consistent with other observations and the model in order to dynamically account for changes in biases (Derber and Wu 1998; Dee and Uppala 2009). Both variational bias correction and the ingestion of raw radiances have a stronger impact on the environment than the TC since the assimilation of satellite data can be severely limited by clouds and precipitation (Andersson et al. 2005). In fact, the ERA-I is the only reanalysis that assimilates radiances affected by clouds and precipitation (Dee et al. 2011) either directly or indirectly through a 1DVAR + 4DVAR approach (Bauer et al. 2006a,b). Additional improvements specifically found for the ERA-I over the ERA-40 include a better formulation of the background error constraint, a new humidity analysis, improvements in the quality control of the input data, and better model physics that include an improved radiative transfer model (Simmons et al. 2007; Dee et al. 2011). Lastly, MERRA employs an incremental analysis update (IAU) that gradually corrects the forecast model through an additional model tendency term implemented during a second hindcast, which reduces model shock (Bloom et al. 1996). Additionally, the spindown of the Hadley cell that occurs within reanalyses as a result of excessive precipitation (Andersson et al. 2005) is also lessened through the use of the IAU (Rienecker et al. 2011).

The time period from 1979 to 2001 is chosen for study to provide maximum overlap among reanalyses and for coinciding with the satellite era. It should be noted that the ERA-I is only available beginning in 1989 at the time of this research, although it is examined here for completeness. The comparisons provided in this study do not account for the exclusion of earlier years (1979–88) by the ERA-I during which the observing system was inferior (Uppala et al. 2005; Dee and Uppala 2009; Rienecker et al. 2011). The EPAC, NATL, and WPAC are selected for the purposes of brevity and to avoid the larger uncertainty of Best-Track data within other basins (Landsea et al. 2006). Data used to evaluate TC location and intensity are from the NHC Best-Track dataset within the EPAC and NATL and the Joint Typhoon Warning Center (JTWC) Best-Track dataset (Chu et al. 2002) within the WPAC. Despite the fact that the Best-Track is currently the most accurate and comprehensive archive of TC position and intensity, it is still prone to considerable uncertainty given that the dataset is partially derived from a forecaster's subjective estimate (e.g., Landsea et al. 2004). It should also be noted that Best-Track mean sea level pressure (MSLP<sub>min</sub>) is unavailable for many TCs within each basin such that computations involving MSLP<sub>min</sub> consist of a smaller subset of storms (36.6% of total TCs from 1979 to 2001; 48.4% of total TCs from 1989 to 2001). The extended Best-Track dataset (Demuth et al. 2009) is also used in this study to permit comparison of TC size to the variability of TC position difference and intensity. However, the limited availability of extended Best-Track data restricts the results to evaluating TC size data from 1988 to 2001 within the NATL.

### b. Method

TCs are tracked manually according to the methodology of Manning and Hart (2007) who utilized MSLP<sub>min</sub> and maximum 925-hPa relative vorticity to locate the TC using the Best-Track position as the first guess. Manual tracking is preferred here given that choosing an objective threshold for automatic tracking algorithms is difficult owing to the dependence of these thresholds on the resolution of the dataset (Walsh et al. 2007) as was previously discussed (e.g., Uppala et al. 2004; Onogi et al. 2007). It should be noted that some TCs are unable to be manually tracked (0.16% to 1.37% of 6-h Best-Track data; this and all subsequently presented ranges are the minimum and maximum values from the five reanalyses for a given parameter unless explicitly mentioned otherwise) due to the inability to locate an MSLPmin or relative vorticity maxima within the reanalysis. Only Best-Track entries that are able to be tracked within all five reanalyses are included in the analysis performed here. Along with the position of the reanalysis TC,  $VMAX_{10m}$ and MSLP<sub>min</sub> within a  $7^{\circ} \times 7^{\circ}$  box surrounding the analyzed TC center are recorded for each TC that is able to be tracked. To facilitate the diagnosis of relationships with Best-Track TC intensity, both position difference and reanalysis TC intensity are binned into four categories stratified according to Best-Track intensity: tropical depressions (VMAX<sub>10m</sub> < 34 kt), tropical storms  $(34 \text{ kt} \le \text{VMAX}_{10\text{m}} < 64 \text{ kt})$ , category 1–2 TCs (64 kt  $\le$ VMAX<sub>10m</sub> < 96 kt), and category 3–5 TCs (VMAX<sub>10m</sub>  $\geq$ 96 kt). It should be noted that all significance testing and calculation of standard errors in this study conservatively utilize the number of distinctly named TCs

for the sample size rather than the number of 6-h Best-Track points since the latter quantity is highly interdependent. In particular, a given TC will only be counted once for each intensity bin that it falls within during its lifetime regardless of how many 6-h Best-Track data points occur within a given bin. As an example, NATL TC Andrew (1992) is counted only once for each of the four intensity bins since it spent at least one Best-Track time within each bin while strengthening to category 5 intensity.

To quantify the spatial variability of a given quantity, gridded maps with a horizontal resolution of 2° latitude by 2° longitude are constructed. Specifically, maps are made for mean position difference, mean VMAX $_{10m}$ , mean MSLP<sub>min</sub>, correlation coefficients calculated between Best-Track and reanalysis VMAX<sub>10m</sub>, and correlation coefficients computed between Best-Track and reanalysis MSLP<sub>min</sub>. For the gridded maps of mean position difference and mean intensity, the value at each grid point is a weighted average of all TCs passing within 250 km using a Cressman weighting (Cressman 1959). Gridded maps of correlation coefficients computed between Best-Track and reanalysis TC intensity use all TCs passing within 250 km of a given grid point. Mean values and correlation coefficients are only calculated for locations in which at least three distinctly named TCs are found for a grid point. The computation of correlation coefficients also requires at least 10 Best-Track entries present at a grid point.

Further exploration of the variability of mean position difference, mean VMAX<sub>10m</sub>, and mean MSLP<sub>min</sub> is undertaken by correlating these quantities with Best-Track age, Best-Track latitude, Best-Track MSLPmin, Best-Track VMAX<sub>10m</sub>, extended Best-Track radius of 34-kt winds (EBTR<sub>34</sub>), and the distance of the Best-Track TC relative to the location of minimum position difference in each basin within the ERA-40, ERA-I, and MERRA (denoted by circles in Fig. 1). The latter quantity serves as a proxy for observation density in the ERA-40, ERA-I, and MERRA given that regions of minimum position difference in the NATL and WPAC are generally collocated with areas of high observation density (Hatsushika et al. 2006; Manning 2007). In this study, Best-Track age is defined according to the definition given by Kossin et al. (2007) as the time since the TC first reached tropical storm intensity (VMAX<sub>10m</sub>  $\ge$  34 kt). For the purposes of this study, the radius of 34-kt winds is used as a metric for TC size because of its stronger correlation with intensity within the Best-Track and reanalyses (e.g.,  $0.53 \le R \le$ 0.70 for VMAX<sub>10m</sub> and the radius of 34-kt winds as seen in Table 3) in contrast to the radius of the outermost closed isobar (0.34  $\leq R \leq$  0.46 for VMAX<sub>10m</sub> and the radius of the outermost closed isobar which is not shown). It should be noted that while there are several metrics that could be used to quantify TC size (e.g., radius of 34-kt winds, radius of outermost closed isobar), these quantities are not necessarily equivalent (Merrill 1984). In this study, correlation coefficients computed for all TCs are only considered significant when the majority of entries approximately exceed a threshold of R = 0.30. Although the sample sizes are large enough to make the correlation coefficients statistically significant at lower values, R = 0.30 is chosen as the threshold for meaningful correlations so as to narrow the focus of this study. Lastly, differences in the mean evolution of TC intensity with Best-Track age are examined in the reanalyses and the Best-Track by normalizing intensity within each dataset by the climatological standard deviation before binning and averaging each value according to its maximum lifetime Best-Track intensity and Best-Track age.

### 3. Results

### a. Position differences

# 1) SPATIAL VARIABILITY OF POSITION DIFFERENCES

Several important similarities among reanalyses are found in the spatial variability of mean position differences in Fig. 1. First, position differences are generally found to decrease from southeast to northwest within the NATL and WPAC in the ERA-40, ERA-I, and MERRA. Specifically, mean reanalysis TC position is biased southwestward relative to the Best-Track within the NATL and WPAC in these three datasets. All three of these reanalyses exhibit a minimum in position difference within the NATL (WPAC) that occurs over the northeastern United States (northeastern China), which is approximately coincident with the region of highest observation density in the basin (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008). Position difference also appears to isotropically decrease toward these areas of minimum position difference suggesting that the increasing density of observations that occurs towards these landmasses is helping to correct TC position. Correlation coefficients calculated to quantify the relationship between position difference and the location of the Best-Track TC relative to these areas of minimum position difference yield values ranging between 0.27 and 0.38 (Table 2). Although these correlations are relatively weak, they seem to indicate that observation density partially determines the magnitude of position difference (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008).

The reduction of position differences from southeast to northwest in the NATL and WPAC within these three



FIG. 1. Plan view of the magnitude (shaded) and vector (arrow) mean position differences (km) for the (a) CFSR, (b) ERA-40, (c) ERA-I, (d) JRA-25, and (e) MERRA for TCs passing within 250 km of each grid point in the EPAC, NATL, and WPAC. Position difference is defined as the difference between the Best-Track and reanalysis TC position. Vectors point from the Best-Track to the reanalysis TC position from tail to head with the length of the vector proportional to the magnitude of the difference. Vectors are not drawn for mean position difference magnitudes less than 100 km. The black circles denote the mean location of minimum position differences in the ERA-40, ERA-I, and MERRA for each basin. Position difference is interpolated to a 2° latitude by 2° longitude grid with each grid point representing the average of the position difference weighted by its distance from the grid point. Mean position differences are provided only at grid points at which at least three distinctly named TCs are found. The grid is smoothed once with a nine-point smoother.

TABLE 2. Correlation coefficients calculated between TC position difference for TCs from the EPAC, NATL, and WPAC in the CFSR, ERA-40, ERA-1, JRA-25, and MERRA with reanalysis TC VMAX<sub>10m</sub> (Reanalysis VMAX<sub>10m</sub>), reanalysis TC MSLP<sub>min</sub> (Reanalysis MSLP<sub>min</sub>), and the distance of the Best-Track TC relative to the location of mean minimum TC position difference in each basin (Relative location). The mean minimum TC position difference within each basin is calculated from its mean location in the ERA-40, ERA-I, and MERRA given its strong correlation with observation density in these datasets. The first correlation coefficient is for only EPAC TCs (N = 391 in CFSR, ERA-40, JRA-25, and MERRA; N = 230 in ERA-I), the correlation coefficient following the first slash is for only NATL TCs (N = 316 in CFSR, ERA-40, JRA-25, and MERRA; N = 178 in ERA-I), and the correlation coefficient following the second slash is for only WPAC TCs (N = 676 in CFSR, ERA-40, JRA-25, and MERRA; N = 178 in ERA-I). Italics denote where correlation coefficients are significantly different from zero at the 95% confidence level while boldface denote where correlation coefficients are significantly different from zero at the 99% confidence level.

Dataset	Reanalysis VMAX <sub>10m</sub>	Reanalysis MSLP <sub>min</sub>	Relative location
CFSR	-0.22/-0.31/-0.27	0.23/0.18/0.16	0.04/0.12/0.15
ERA-40	-0.11/- <b>0.25</b> /- <b>0.17</b>	0.16/0.18/0.33	-0.03/ <b>0.38/0.31</b>
ERA-I	-0.24/-0.26/-0.22	0.24/0.23/0.32	0.04/ <b>0.29/0.28</b>
JRA-25	- <b>0.22</b> /- <b>0.24</b> /-0.04	0.12/0.01/0.08	0.00/0.11/ <b>0.11</b>
MERRA	-0.30/-0.36/-0.30	0.26/0.30/0.40	0.05/ <b>0.38/0.27</b>

datasets could be due to several factors. One potential influence is the relative sparseness of in situ observations in the eastern NATL and WPAC (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008). Given that track is largely a time integral of steering flow especially in a coarse reanalysis, small deviations in the steering flow over time without observations to correct the position of the TC could be responsible for significant track displacements. Furthermore, displacements in TC position could result in a storm that is stronger (weaker) than observed if it moves into a more (less) favorable environment than in reality. These resulting errors in reanalysis TC intensity due to position difference may further feedback onto position difference due to the positive correlation between intensity and the depth of the steering flow within models (Dong and Neumann 1986; Velden 1993). Incorrect tracks could also potentially result from the misrepresentation of interactions between TCs and larger scales due to the TC being incorrectly located. In addition to being responsible for increased track errors in the southeastern portion of the basin, the feedbacks associated with track errors may also explain why the relationship between TC position difference and reanalysis TC MSLP<sub>min</sub> or VMAX<sub>10m</sub> is relatively weak (Table 2). Specifically, with the exception of the MERRA, the magnitude of correlation coefficients between TC position difference and reanalysis TC intensity is generally smaller than 0.30 in the majority of reanalyses. Additionally, any correlations that may exist could be the result of stronger TCs being easier to track than less intense storms, given the diffuse structure of weaker storms. Lastly, the improper depiction of TC beta gyres (Chan and Williams 1987; Fiorino and Elsberry 1989) owing to the coarse resolution of the reanalyses may also yield a southeastward displacement of reanalysis TCs relative to the Best-Track due to an underestimation of the resulting northwestward self-propagation in the Northern Hemisphere.

In spite of the fact that correlations are small between position difference and Best-Track TC intensity (not shown), position difference is found to decrease substantially for stronger Best-Track TC intensities, as seen in Fig. 2a. Specifically, category 3–5 TCs have mean position differences that are 25% smaller than tropical depressions in the ERA-40, ERA-I, and MERRA. The smaller mean position differences as well as the lower standard deviations may be explained by the fact that a larger fraction of Best-Track major TCs generally occurs in more observation dense portions of the NATL and WPAC (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008) improving TC track. A secondary factor may be due to Best-Track TCs with stronger VMAX<sub>10m</sub> (MSLP<sub>min</sub>) having larger median EBTR<sub>34</sub> (Kimball and Mulekar 2004), which is also supported by the correlations in Tables 3 and 4 (R = 0.56 for VMAX<sub>10m</sub>; R = -0.59 for MSLP<sub>min</sub>). These strong correlations imply that more intense TCs are better sampled by observations due to their larger size which may help to correct their position. Furthermore, reanalysis TC intensity also appears to suffer more for TCs with smaller EBTR<sub>34</sub> (Tables 3 and 4) potentially feeding back onto position differences. Smaller, weaker TCs may also have larger position differences due to reanalyses being unable to properly resolve the impact of TC beta gyres on storm motion. In contrast to the ERA-40, ERA-I, and MERRA, the CFSR and JRA-25 exhibit relatively small changes in TC position differences across each basin. The smaller magnitude and lack of significant gradients in position difference is seemingly attributable to the use of vortex relocation within the CFSR and TC wind profile retrievals within the JRA-25.

In addition to position differences being maximized in the southeastern portion of the NATL and WPAC, a



FIG. 2. Box and whiskers plots of (a) position difference magnitude (km), (b) VMAX<sub>10m</sub> (kt), and (c) MSLP<sub>min</sub> (hPa) for TCs in the EPAC, NATL, and WPAC for each of the five reanalyses stratified by the four Best-track intensity categories used in this study. The CFSR, ERA-40, ERA-I, JRA-25, and MERRA correspond with color coding of blue, red, green, cyan, and orange, respectively. The mean of the sample is denoted by a white square printed within each box. The number of distinctly named TCs for the CFSR, ERA-40, JRA-25, and MERRA is denoted at the top of the figure for each intensity category while the number of distinctly named TCs for the ERA-I is given in parentheses. The dashed lines connect the mean of each intensity category for each reanalysis to help identify relationships between each parameter and Best-track TC intensity.

TABLE 3. Correlation coefficients calculated between VMAX<sub>10m</sub> for TCs from the EPAC, NATL, and WPAC in the CFSR, ERA-40, ERA-I, JRA-25, MERRA, and Best-Track with EBTR<sub>34</sub>, Best-Track VMAX<sub>10m</sub> (BT VMAX<sub>10m</sub>), Best-Track latitude (BT<sub>Lat</sub>), and Best-Track age (BT<sub>Age</sub>). The first correlation coefficient is for only EPAC TCs (N = 391 in CFSR, ERA-40, JRA-25, and MERRA; N = 230 in ERA-I), the correlation coefficient following the first slash is for only NATL TCs (N = 316 in CFSR, ERA-40, JRA-25, and MERRA; N = 178 in ERA-I), and the correlation coefficient following the second slash is for only WPAC TCs (N = 676 in CFSR, ERA-40, JRA-25, and MERRA; N = 178 in ERA-I). Correlation coefficients for EBTR<sub>34</sub> are computed for a smaller subset consisting of NATL TCs from 1988–2001 appearing in the extended Best-Track. NA denotes that correlation coefficients are not computed between the quantities in question. Italics denote where correlation coefficients are significantly different from zero at the 95% confidence level while boldface denote where correlation coefficients are significantly different from zero at the 99% confidence level.

Dataset	EBTR <sub>34</sub>	BT VMAX <sub>10m</sub>	BT <sub>Lat</sub>	BT <sub>Age</sub>
CFSR	NA/ <b>0.57</b> /NA	0.36/0.61/0.57	-0.01/ <b>0.22/0.17</b>	0.23/0.34/0.36
ERA-40	NA/ <b>0.53</b> /NA	0.20/0.45/0.38	-0.09/ <b>0.31/0.25</b>	-0.01/0.25/0.30
ERA-I	NA/ <b>0.61</b> /NA	0.26/0.47/0.40	0.11/0.34/0.22	0.10/0.38/0.37
JRA-25	NA/ <b>0.65</b> /NA	0.57/0.73/0.70	0.22/0.37/0.33	0.24/0.38/0.38
MERRA	NA/ <b>0.70</b> /NA	0.26/0.51/0.42	0.14/0.48/0.44	0.16/0.47/0.38
Best track	NA/ <b>0.56</b> /NA	1.00/1.00/1.00	0.03/0.12/0.03	0.07/0.25/0.22

second region of relatively larger position differences is present in the northeastern portion of the NATL and WPAC. Generally, reanalysis TCs in this area are displaced westward compared to the Best-Track (Fig. 1). One factor possibly responsible for this maximum in position difference is the low density of observations found in this region (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008). Among plausible secondary influences is the climatological preference for the interaction of extratropical cyclones and TCs to occur in the northern NATL and WPAC (Hart and Evans 2001; Jones et al. 2003), which may displace the analyzed reanalysis TC position toward the extratropical cyclone. An additional factor is the proximity of TCs to well-resolved, large-scale low pressure areas (e.g., Aleutian low, Icelandic low), which may shift the reanalysis TC location toward these regions of low pressure.

A third area of substantially larger TC position differences within each reanalysis, except in the JRA-25, is the EPAC (Fig. 1). Mean position differences are as large as 400 km in the ERA-40, 400 km in MERRA, and 300 km in the ERA-I. These position differences generally exhibit a southeastward displacement in reanalysis TC position relative to the Best-Track. Statistically insignificant correlation coefficients (R < 0.05, Table 2) are found between position difference and the location of the Best-Track TC relative to the area of minimum position difference in the EPAC. Such a result is expected given the absence of a relatively observation dense region in this basin (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008). Moreover, while NATL and WPACTCs are moving toward the most observationally dense region in the basin allowing position to be gradually corrected over time, EPAC TCs are moving away from the most observation-rich region within the basin conceivably causing degradation in position over the lifespan of the TC. Further, the southeastward displacement of reanalysis TCs relative to the Best-Track may be indicative of a slightly weaker subtropical high that potentially results from the inability of reanalyses to capture the feedbacks between TCs and the larger scales. The particularly poor representation of reanalysis TC intensity (section 3b) in the EPAC also may contribute to the larger position differences given the correlations between position difference and reanalysis TC intensity (Tables 3 and 4).

An additional factor influencing position differences in the EPAC is the elevated terrain found upstream of the basin in Mexico. Previous work has argued that this complex topography plays an important role in dictating whether TCs move westward toward the central Pacific or recurve into Mexico (Zehnder 1993). In light of this fact and the likelihood that reanalyses cannot adequately resolve this mountainous terrain, it seems probable that the effects of elevated topography on TC tracks are

TABLE 4. As in Table 3 but for correlation coefficients computed between MSLP<sub>min</sub> for TCs from the EPAC and NATL and each of the parameters given in Table 3 except Best-Track VMAX<sub>10m</sub>, which is replaced by Best-Track MSLP<sub>min</sub> (BT MSLP<sub>min</sub>). The first correlation coefficient is for only EPAC TCs (N = 212 in CFSR, ERA-40, JRA-25, and MERRA; N = 198 in ERA-I) while the correlation coefficient following the slash is for only NATL TCs (N = 244 in CFSR, ERA-40, JRA-25, and MERRA; N = 153 in ERA-I). WPAC TCs are excluded from these computations given that Best-Track MSLP<sub>min</sub> is widely unavailable in this basin.

Dataset	EBTR <sub>34</sub>	BT MSLP <sub>min</sub>	BT <sub>Lat</sub>	BT <sub>Age</sub>
CFSR	NA/- <b>0.71</b>	0.43/0.61	-0.09/-0.29	-0.14/- <b>0.39</b>
ERA-40	NA/-0.53	0.29/0.46	0.03/-0.24	0.19/-0.26
ERA-I	NA/-0.60	0.30/0.48	-0.11/- <b>0.29</b>	0.06/- <b>0.35</b>
JRA-25	NA/-0.70	0.59/0.70	-0.09/-0.31	0.09/- <b>0.36</b>
MERRA	NA/-0.66	0.33/0.50	-0.13/- <b>0.36</b>	0.08/- <b>0.39</b>
Best track	NA/-0.59	1.00/1.00	0.02/-0.10	-0.06/- <b>0.31</b>

misrepresented and that the resulting position differences likely cannot be corrected owing to the relative lack of observations in the EPAC (D. Kleist 2011, personal communication). Lastly, it remains plausible that the poorly resolved topography may result in a higher rejection rate of valid observations in this basin further degrading TC track.

# 2) COMPARISON OF POSITION DIFFERENCES AMONG REANALYSES

Dissimilarities in TC position difference among the reanalyses can be found in Fig. 2a. Of the five reanalysis datasets, the ERA-40 and CFSR are found to have the largest and smallest position differences, respectively. As expected, the use of vortex relocation in the CFSR and TC wind profile retrievals within the JRA-25 lead to TC position differences that are much smaller than for the ERA-40, ERA-I, and MERRA. These two methodologies also yield smaller variability in position differences with increasing intensity than either the ERA-40, ERA-I, or MERRA as evidenced by the lower standard deviations.

A more uniform way to analyze position differences is by normalizing them by the horizontal grid resolution of the reanalysis (Table 5). Assuming perfect representation of TC tracks within each reanalysis and the Best-Track, mean normalized TC position differences should be less than half of the length of a diagonal of a gridbox  $(0.71\Delta x)$  because of the limitations of representing TC position on a discrete grid. However, only the JRA-25 is below this threshold for all Best-Track intensity bins. Mean normalized TC position differences show that the MERRA has the largest differences of all datasets ranging between  $2.12\Delta x$  and  $2.92\Delta x$  (149 and 205 km). In comparison, the JRA-25 has mean differences ranging between  $0.43\Delta x$  and  $0.67\Delta x$  (57 and 88 km), which is nearly 2.5 times smaller than the CFSR (0.81 $\Delta x$  and  $1.60\Delta x$ ; 43 and 84 km). This result is suggestive of the particular effectiveness of TC wind profile retrievals in the JRA-25 at reducing position difference relative to the use of vortex relocation in the CFSR.

Further examination of the three remaining reanalyses shows that mean position differences in the MERRA are at most 25 km smaller than the ERA-40 (164 and 214 km; Fig. 2a). Given the relatively high grid resolution of the MERRA, these mean position differences yield normalized values that are substantially larger (0.74 and 1.11  $\Delta x$ larger; Table 5) than those within the ERA-40. Additionally, mean position differences in the ERA-I (100 and 154 km) are found to be 60 and 65 km smaller than in the ERA-40 for each intensity bin. While these reduced position differences imply substantial improvement of the ERA-I relative to the ERA-40, normalized

TABLE 5. TC position differences normalized by the horizontal resolution of the corresponding reanalysis for the four Best-Track intensity bins for TCs from the EPAC, NATL, and WPAC in the CFSR, ERA-40, ERA-I, JRA-25, and MERRA. The first number is the mean normalized position difference and the second number is the standard error of the mean of each subset.

Dataset	Tropical depression	Tropical storm	Category 1–2	Category 3–5
CFSR	$1.60\pm0.05$	$1.26 \pm 0.04$	$0.93\pm0.05$	$0.81 \pm 0.08$
ERA-40	$1.81 \pm 0.04$	$1.63 \pm 0.04$	$1.49\pm0.04$	$1.38 \pm 0.05$
ERA-I	$2.09 \pm 0.05$	$1.81 \pm 0.05$	$1.50 \pm 0.05$	$1.35 \pm 0.07$
JRA-25	$0.67\pm0.02$	$0.51 \pm 0.01$	$0.46\pm0.01$	$0.43 \pm 0.01$
MERRA	$2.92\pm0.06$	$2.59\pm0.05$	$2.25\pm0.07$	$2.12 \pm 0.09$

mean values exhibit only small discrepancies between the two datasets with maximum differences of  $0.28\Delta x$ . These results are suggestive of little relative reduction in mean position differences between these datasets. The larger position differences in the ERA-40, ERA-I, and MERRA compared to the CFSR and JRA-25 suggests that the use of methodologies that explicitly correct TC location trump all other improvements (e.g., 4DVAR, increased horizontal resolution, improved microphysics).

#### b. Intensity

#### 1) SPATIAL VARIABILITY OF INTENSITY

The coarse resolution of reanalyses generally precludes their replication of Best-Track TC intensity (Walsh et al. 2007) instead yielding only modest changes in reanalysis TC intensity compared to the Best-Track. Figures 3 and 4 show mean VMAX<sub>10m</sub> and MSLP<sub>min</sub> in the EPAC, NATL, and WPAC for the Best-Track and reanalyses. As a note, WPAC TCs have mean values of MSLPmin that are stronger than EPAC and NATL TCs as a result of the lower environmental pressure (Dvorak 1975; Knaff and Zehr 2007). With the exception of the CFSR within the NATL and WPAC, substantial portions of each basin within the remaining reanalyses have mean VMAX<sub>10m</sub> that fail to meet the Best-Track tropical depression threshold (30 kt). Furthermore, while mean values of Best-Track intensity are typically maximized in the central portion of the EPAC, NATL, and WPAC, reanalyses exhibit peak values that are displaced northward in the latter two basins and zonally within the EPAC (Figs. 3 and 4).

Although reanalyses are unable to resolve Best-Track TC intensity, these datasets would still be of some utility if the spatial variability of reanalysis TC intensity is well correlated to the Best-Track (thus providing for a useful bias-corrected relationship). To examine this idea, correlation coefficients are calculated between Best-Track and reanalysis TC VMAX<sub>10m</sub> (MSLP<sub>min</sub>) yielding values between 0.20 and 0.73 (0.29 and 0.70) as seen in Table 3



FIG. 3. Plan view of mean VMAX<sub>10m</sub> (kt) for TCs from the (a) CFSR, (b) ERA-40, (c) ERA-I, (d) JRA-25, (e) MERRA, and (f) Best-Track for TCs passing within 250 km of each grid point in the EPAC, NATL, and WPAC. VMAX<sub>10m</sub> is interpolated to a  $2^{\circ}$  latitude by  $2^{\circ}$  longitude grid with each grid point representing the average of VMAX<sub>10m</sub> weighted by its distance from the grid point. Mean VMAX<sub>10m</sub> is provided only at grid points at which at least three distinctly named Best-Track TCs are found. The grid is smoothed once with a nine-point smoother.



FIG. 4. As in Fig. 3 but for MSLP<sub>min</sub> (hPa) within the EPAC and NATL. Note that mean values are not computed within the WPAC due to the lack of availability of Best-Track MSLP<sub>min</sub> within this basin.

(Table 4). Significant variability is noted among basins with the strongest (weakest) relationships found in the NATL (EPAC). In particular, correlation coefficients in the NATL typically explain nearly 15% (13%) more of the variance than EPAC TCs for VMAX<sub>10m</sub> (MSLP<sub>min</sub>). The lower correlations in the EPAC may be attributable to the sparseness of observations or the movement of TCs away from the most observation dense portion of the basin making it difficult for observations to nudge reanalysis TC intensity toward the correct intensity. Moreover, the smaller size of EPAC TCs (Chavas and Emanuel 2010) may also degrade reanalysis TC intensity given the positive correlation between EBTR<sub>34</sub> and reanalysis TC intensity (Tables 3 and 4). A third factor may be the inability to resolve the effects of elevated terrain on TCs, which include serving as an important player in the genesis and intensification of TCs near the Mexican coast (Zehnder 1991; Turk et al. 1995; Mozer and Zehnder 1996; Farfán and Zehnder 1997; Zehnder et al. 1999; Molinari et al. 2000). The lack of observations in this region (which may otherwise have helped compensate for the inability of the reanalysis to resolve the complex topography) may prevent TC intensity from being nudged closer to its Best-Track value (D. Kleist 2011, personal communication). Lastly, it remains plausible that TC intensity is weaker due to the speculated larger rejection rate of observations in the EPAC that results from the mountainous terrain.

Significant variability of correlation coefficients between Best-Track and reanalysis TC intensity is also observed among datasets. In particular, the CFSR and JRA-25 exhibit stronger mean intensities and larger correlations with the Best-Track than either the ERA-40, ERA-I, or MERRA. The variance explained by these relationships is at least 6% (8%) and 26% (24%) larger in the CFSR and JRA-25 for VMAX<sub>10m</sub> (MSLP<sub>min</sub>), respectively, relative to the other three reanalyses suggesting the value of supplementing reanalyses with Best-Track data to improve intensity. Additionally, the ERA-40, ERA-I, and MERRA have smaller correlation coefficients of similar magnitude with the Best-Track implying that the improvements found in the ERA-I and MERRA over the ERA-40 do not significantly affect reanalysis TC intensity. These results argue that reanalyses are able to represent the variability of Best-Track intensity with moderate success given that the explained variance is as high as 53%.

To further explore the variability of reanalysis TC intensity, gridded maps of correlation coefficients between reanalysis and Best-Track TC VMAX<sub>10m</sub> (MSLP<sub>min</sub>) are presented in Fig. 5 (Fig. 6). The majority of all three basins exhibit moderately strong correlations ( $R \ge 0.60$ ) in the JRA-25, while robust correlations within the CFSR and MERRA are found only within the NATL. None of the three basins within the ERA-I or ERA-40 exhibits strong correlations in the majority of any basin. Examining the spatial variation of correlation coefficients among basins demonstrates that correlations within the NATL are generally larger than those in the WPAC with even smaller magnitudes in the EPAC (Figs. 5 and 6). The smaller values in the WPAC could be due to the stronger mean Best-Track intensity of TCs, which is more difficult to resolve or deficiencies in observation coverage (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008).

### 2) RELATIONSHIP BETWEEN LATITUDE AND TC SIZE ON REANALYSIS TC INTENSITY

Several of the factors responsible for small correlation coefficients between Best-Track and reanalysis TC intensity in the NATL and WPAC likely are associated with nonphysical increases in reanalysis TC intensity from south to north. As seen in Tables 3 and 4, correlation coefficients between reanalysis VMAX<sub>10m</sub> (MSLP<sub>min</sub>) and Best-Track latitude range between 0.17 and 0.48 (-0.36 and -0.24) compared to significantly lower correlations of 0.03 and 0.12 (-0.10 and 0.02) in the Best-Track. Correlations are observed to be slightly stronger within the NATL than the WPAC with smaller values in the EPAC.

Potential explanations for the large correlation between reanalysis TC intensity and Best-Track latitude include the relatively greater observation density within midlatitudes (Hatsushika et al. 2006; Manning 2007; Vecchi and Knutson 2008), which may nudge reanalysis TCs toward slightly stronger intensities. A second plausible explanation is that increases in reanalysis horizontal resolution with latitude (approximately 16% increase from the equator to 30°N) may allow TCs to become better resolved with poleward motion. A third factor may be that the greater frequency of extratropical transition occurring at higher latitudes (Hart and Evans 2001; Jones et al. 2003) results in the expansion of the TC wind field (Evans and Hart 2008) conceivably making these storms both easier to resolve and better sampled by observations. Lastly, erroneous values of TC intensity could be introduced due to the methodology used since no attempt is made to discriminate whether a given intensity value is associated with the TC in question or a separate entity (e.g., nearby fronts, extratropical cyclones).

A second potential factor contributing to the lack of stronger correlations between Best-Track and reanalysis TC intensity is observed TC size. Correlations between EBTR<sub>34</sub> and reanalysis TC intensity yield values between 0.53 and 0.70 (-0.71 and -0.53) for VMAX<sub>10m</sub> (MSLP<sub>min</sub>; Tables 3 and 4) representing the strongest relationship between TC intensity and any other parameter. While



FIG. 5. Plan view of the correlation coefficients between Best-Track and reanalysis VMAX<sub>10m</sub> for TCs passing within 250 km of each grid point in the EPAC, NATL, and WPAC for a  $2^{\circ}$  latitude by  $2^{\circ}$  longitude grid. Hatching represent values of correlation coefficients that are significantly different from zero at the 99% confidence level. Correlation coefficients are computed only at grid points at which at least three distinctly named Best-Track TCs and 10 Best-Track entries are found. The grid is smoothed once with a nine-point smoother.



FIG. 6. As in Fig. 5 but for correlation coefficients calculated between Best-Track and reanalysis MSLP<sub>min</sub>. Note that mean values are not computed within the WPAC due to the lack of availability of Best-Track MSLP<sub>min</sub> within this basin.

these correlations are either comparable or larger than those in the Best-Track, that they are at least equivalent in magnitude is significant since mean reanalysis VMAX<sub>10m</sub> is generally less than 34 kt in all reanalyses except Best-Track hurricane strength TCs in the CFSR and JRA-25. What is likely occurring is that larger values of EBTR<sub>34</sub> are acting as proxies for weaker, more easily resolvable, gradients between the TC inner core and its environment. Additionally, these TCs may be more thoroughly sampled by the observing system with increasing size. Increases in EBTR<sub>34</sub> with latitude (Merrill 1984; Kimball and Mulekar 2004; Kossin et al. 2007) may also suggest that observed changes in TC size are yielding increases in reanalysis TC intensity with latitude.

### 3) COMPARISON OF INTENSITIES AMONG REANALYSES

To explore mean dataset differences among reanalysis TCs, mean VMAX<sub>10m</sub> and MSLP<sub>min</sub> are presented for the four intensity bins in Figs. 2b and 2c. The ERA-40, ERA-I, JRA-25, and MERRA have approximately the same VMAX<sub>10m</sub> for Best-Track tropical depressions ranging from 19.7 to 21.4 kt. In contrast, the CFSR is noted to have a mean intensity (27.8 kt) over 6 kt stronger than the other datasets for Best-Track tropical depressions comparable to the mean Best-Track value of 30 kt. For comparison, MSLP<sub>min</sub> of Best-Track tropical depressions within the five datasets are approximately within 1 hPa of each other ranging between 1006.3 and 1007.3 hPa, which is similar to the mean Best-Track value of 1006.5 hPa. The underestimation of only mean VMAX<sub>10m</sub> suggests that the coarse resolution of reanalyses prevents these datasets from maintaining the pressure gradients necessary to sustain Best-Track values of VMAX<sub>10m</sub>.

As Best-Track intensity increases, the coarse resolution of reanalyses results in the severe underestimation of both VMAX<sub>10m</sub> and MSLP<sub>min</sub>. Such a result is expected since the wind maximum in real hurricanes becomes confined to increasingly smaller scales as the TC intensifies (e.g., Kimball and Mulekar 2004), making a fixed resolution reanalysis grid increasingly less likely to resolve VMAX $_{10m}$ , yielding an increasingly large bias in intensity. These discrepancies are most noticeable for category 3-5 TCs in which mean reanalysis VMAX<sub>10m</sub> is between 27.8 and 47.5 kt compared to the mean Best-Track value of 115.6 kt. Of the five reanalyses, the CFSR and JRA-25 have substantially larger VMAX<sub>10m</sub> compared to the remaining reanalyses with differences of at least 16.4 and 6.5 kt, respectively. While mean MSLP<sub>min</sub> within the CFSR and JRA-25 are close to each other in magnitude at 993.2 and 993.8 hPa, respectively, the remaining three reanalyses have mean MSLP<sub>min</sub> that are greater than these two datasets with values ranging between 997.4 and 999.9 hPa. The large disparities between the CFSR and JRA-25 with the rest of the reanalyses appear to be due to the use of vortex relocation and TC wind profile retrievals, respectively. Similar to VMAX<sub>10m</sub>, mean reanalysis TC MSLP<sub>min</sub> is significantly weaker than the mean Best-Track MSLP<sub>min</sub> (946.3 hPa) for category 3–5 TCs.

A closer examination of the intensity of reanalysis TCs reveals that their underrepresentation is beyond what can be attributed to the coarse resolution of the reanalyses (Walsh et al. 2007). Specifically, benchmarks of VMAX<sub>10m</sub> provided by Walsh et al. (2007) for tropical storm strength TCs resampled to the resolution of the five reanalyses range between 28.8 and 33.4 kt compared to actual values of reanalysis VMAX<sub>10m</sub> with magnitudes between 20.8 and 29.9 kt. Several factors may potentially be responsible for the underestimation of VMAX<sub>10m</sub> beyond that due to the coarse resolution of the reanalyses including the choice of model physics and the manner in which available observations are assimilated. To quantify these effects on more intense TCs, Walsh et al. (2007) also provide expected values of observed VMAX $_{10m}$ for NATL TC Andrew (1992) during its peak intensity  $(VMAX_{10m} = 150 \text{ kt}; 1800 \text{ UTC } 23 \text{ August } 1992) \text{ re-}$ sampled to a range of coarser resolutions to serve as a benchmark for models. The horizontal resolution of each of the reanalyses should yield resampled  $VMAX_{10m}$ ranging from approximately 58 to 100 kt. The actual range of VMAX<sub>10m</sub> within the reanalyses is 17.2-38.2 kt, which is well below VMAX<sub>10m</sub> expected as a result of the coarse grid spacing. These results imply that factors outside of resolution conspire to play an even larger role with increasing Best-Track intensity as evidenced by the underestimation of the resampled intensity of 20 kt or more for TC Andrew (Walsh et al. 2007).

### 4) LIFE CYCLE OF TC INTENSITY AMONG BEST-TRACK AND REANALYSES

While an underrepresentation of reanalysis TC intensity beyond that justified by Walsh et al. (2007) has been demonstrated, reanalyses could still be of utility for examining TC intensity if they are able to mimic the evolution of normalized Best-Track TC intensity with age (life cycle of TC intensity). Before analyzing the composite life cycle of normalized TC intensity, it is important to describe the relationship between age and intensity found within the Best-Track. The intensification and subsequent decay of TC intensity during its lifespan suggests that the correlation between Best-Track age and Best-track intensity would be relatively weak. Indeed, the NATL and WPAC exhibit weak correlations between Best-Track TC age and intensity with correlations of 0.25 (-0.31) and 0.22, respectively, for VMAX<sub>10m</sub> (MSLP<sub>min</sub>; Tables 3 and 4) with significantly weaker correlations found in the EPAC (0.07 for VMAX<sub>10m</sub>; -0.06 for MSLP<sub>min</sub>). Of the two basins, the NATL is found to have the strongest linear relationship between Best-Track age and Best-Track intensity. Of the three basins, the EPAC (NATL) displays the propensity to reach peak intensity earliest (latest) on day 3.50 (day 8.00) with respect to the time of genesis in the Best-Track. Best-track EPAC TCs (5.00 days) also tend to have slightly shorter lifespans compared to NATL (5.32 days) and WPAC TCs (5.61 days). The relationship between Best-Track age and reanalysis VMAX<sub>10m</sub> (MSLP<sub>min</sub>), as described by correlation coefficients, is stronger in the NATL and WPAC for all reanalyses except the ERA-40 with values ranging between 0.25 and 0.47 (-0.39 and -0.26). These correlations between Best-Track age and reanalysis TC intensity are generally larger than those between Best-Track age and Best-Track TC intensity. In contrast, all TCs within the EPAC consistently exhibit correlation coefficients with significantly smaller magnitudes than in the Best-Track, implying the absence of any strong relationships.

While the correlation coefficients help quantify the strength of the relationship between age and intensity, they do not capture the nonlinearity between these two parameters. To further explore the relationship between age and intensity in the Best-Track and reanalyses, normalized VMAX<sub>10m</sub> (NVMAX<sub>10m</sub>) for all TCs in the NATL and WPAC are categorized and averaged according to maximum lifetime Best-Track TC intensity and Best-Track age (Fig. 7). Normalized MSLP<sub>min</sub> is not shown but is found to exhibit similar tendencies to NVMAX $_{10m}$ . EPAC TCs are excluded from the calculations given that the relationship between age and intensity is not as robust and the timing of peak intensity differs substantially from the other basins. According to Fig. 7, Best-Track NVMAX10m generally increases more precipitously prior to peak intensity than in the reanalyses  $(0.27\sigma \text{ day}^{-1})$ for the Best-Track versus 0.11 to  $0.21\sigma$  day<sup>-1</sup> for the reanalyses between the time of Best-Track genesis and the time of peak intensity;  $\sigma$  is defined as the standard deviation of intensity within each dataset) reaching maximum values at day 5.50 relative to time of TC genesis. In contrast, reanalyses exhibit peak NVMAX<sub>10m</sub> occurring 7.50 to 11.50 days after Best-Track genesis. The combination of the later time of peak NVMAX<sub>10m</sub> and smaller intensification rates yields a larger peak value of normalized intensity in reanalyses compared to the Best-Track.

These results can generally be extended to each intensity bin found in Figs. 7b–e with the caveat that maximum values of NVMAX<sub>10m</sub> for category 3–5 TCs are stronger in the Best-Track than for the reanalyses. Each intensity bin exhibits Best-Track NVMAX<sub>10m</sub> peaking earlier (between days 1.25 and 3.50) in the composite life cycle for all TC intensity bins. Although reanalysis NVMAX<sub>10m</sub> peaks earlier for each intensity bin than for the composite of all TCs, the maximum value of NVMAX<sub>10m</sub> still occurs later than Best-Track NVMAX<sub>10m</sub> within each bin. Differences in the composite life cycle are most apparent for Best-Track category 3–5 strength TCs given that intensity increases and decreases most strongly in the Best-Track compared to reanalysis TCs, which exhibit longer, more uniform intensification tendencies and shorter intervals of decay.

A number of factors are likely responsible for the stronger than observed nonphysical relationship between Best-Track TC age and reanalysis TC intensity including the occurrence of larger observed TC sizes with increasing Best-Track age (Merrill 1984; Weatherford and Gray 1988; Cocks and Gray 2002; Kimball and Mulekar 2004; Kossin et al. 2007; Chavas and Emanuel 2010), which would yield more easily resolvable TCs. Additionally, more gradual intensification of reanalysis TCs is expected owing to the inability of reanalyses to resolve the TC inner core and the associated nonlinear intensification processes (e.g., Shapiro and Willoughby 1982). Another factor may be that TCs become more intense through the assimilation of observations during each analysis cycle (which are generally more prevalent later in life outside the EPAC) helping to nudge these storms toward stronger intensities over time. If this relationship is important, then the shorter lifespan of TCs may partially explain why storm intensity is muted within the EPAC relative to other basins. Further, the sparseness of observations in the EPAC may be partially responsible for the absence of stronger correlations between age and intensity for reanalysis TCs (Tables 3 and 4). Lastly, many of the plausible explanations for the relationship between reanalysis TC intensity and Best-Track latitude may also be responsible for correlations between reanalysis TC intensity and Best-Track age. Conversely, Best-Track age may be also contributing to the relatively larger correlations between reanalysis TC intensity and Best-Track latitude (Tables 3 and 4) since TCs generally move poleward over time.

### c. Examples of nonphysical TC structure

The extensive evaluation of TC position and intensity presented here made a similar analysis of TC structure beyond the scope of this study. Nonetheless, several examples of nonphysical structures were discovered that are important to document here as they may impact the recommendations provided from exclusively examining TC position and intensity. In particular, a nontrivial fraction of TCs within the CFSR contain significant discontinuities aligned along lines of longitude within the mass and momentum field of the TC (P. Pegion and H. Winterbottom 2011, personal communication). Specific



FIG. 7. Mean life cycle of normalized VMAX<sub>10m</sub> ( $\sigma$ , or standard deviation, of each dataset; lineplot) as a function of Best-Track TC age (days) for TCs within the NATL and WPAC for (a) all TCs, (b) tropical storms, (c) category 1–2 TCs, and (d) category 3–5 TCs for the Best-Track and five reanalyses. Normalized VMAX<sub>10m</sub> is binned according to the maximum Best-Track intensity category that a given TC reaches during its lifetime. Specifically, category 3–5 TCs consist of the mean life cycle of all TCs that have reached the category 3–5 intensity threshold at least once within the Best-Track. The number of distinctly named Best-Track TCs used to calculate the mean normalized VMAX<sub>10m</sub> for each day is given by black bars for the CFSR, ERA-40, JRA-25, and MERRA while the number of distinctly named Best-Track TCs for the ERA-I are represented by gray bars. The CFSR, ERA-40, ERA-I, JRA-25, MERRA, and Best-Track correspond with color coding of blue, red, green, cyan, orange, and light green, respectively. Mean values are only calculated for cases in which 10 distinctly named Best-Track TCs are found. The error bars denote the standard error of the mean.



FIG. 8. Plan view of 925-hPa geopotential height (gpm) for (a) TC Guillermo at 1800 UTC 2 Aug 1997 (Best-Track VMAX<sub>10m</sub> = 105 kt), (b) TC Katrina at 0000 UTC 26 Aug 2005 (Best-Track VMAX<sub>10m</sub> = 70 kt), and (c) TC Orchid at 1200 UTC 4 Oct 1991 (Best-Track VMAX<sub>10m</sub> = 40 kt) in the CFSR. (d) Vertical cross section of geopotential height anomalies (gpm) through the line of latitude (19.5°N) intersecting the center of TC Orchid in (c). Anomalies are computed relative to a CFSR climatology from 1982 to 2001.

examples of these nonphysical structures in three different basins are found in Figs. 8a-c for EPAC TC Guillermo (1997), NATL TC Katrina (2005), and WPAC TC Orchid (1991), respectively. These discontinuities manifest themselves throughout the atmosphere as demonstrated by a vertical cross section (Fig. 8d) corresponding to Fig. 8c. The seemingly systematic nature of these nonphysical structures raises questions as to whether an intercomparison of TC structure among reanalyses would yield similar results to those for track and intensity for the CFSR. A related point of note regarding the CFSR is that the vortex relocation was originally intended to not be used when the vortex was near elevated terrain (elevation greater than 500 m). While mass variables in the CFSR were not relocated under these circumstances, momentum variables were erroneously relocated, potentially introducing an imbalance in the analysis field (D. Kleist 2011, personal communication), which further argues for a separate extensive analysis of reanalysis TC structure.

In contrast to the CFSR, the only physically inconsistent TC structures found within the ERA-I during this cursory check are for TC Flo (1993) as seen in Fig. 9. Specifically, a 101.7-kt wind speed at 10 m (reanalysis  $MSLP_{min} = 987.6 \text{ hPa}$ ) is found on the *western* side of the reanalysis TC, which is not consistent with the mean sea level pressure field (Fig. 9a). Moreover, the 10-m wind speed should not be significantly greater than the wind speed at any vertical level within the lower troposphere (Figs. 9a and 9b) as is found for this particular case. Such a structure is physically inconsistent with a warm-core cyclone given that wind speed should not decrease with height above the surface in the planetary boundary layer. Additionally, the wind maximum should be located on the right side of motion since the storm is moving briskly northeastward at 42.7 kt. Further, the fact that  $VMAX_{10m}$  is over 50 kt higher than the analysis time 6 h prior and after (not shown) further suggests that the structure is nonphysical. For comparison, TC Flo



FIG. 9. Plan view of (a) 10-m wind speed (kt, shaded) and minimum mean sea level pressure (hPa, contours) and (b) 700-hPa wind speed (kt, shaded) and 700-hPa geopotential height (gpm, contours) for Typhoon Flo at 1200 UTC 8 Oct 1993 (Best-Track VMAX<sub>10m</sub> = 60 kt) in the ERA-I. The cyan arrow denotes the direction of motion of the TC, traveling at a speed of 42.7 kt. As a note, the nonphysical maximum on the western side of the TC does not exist either at 6 h prior or after the time in question.

intensified from 55 to 60 kt during the first 6-h period while maintaining a constant intensity during the following 6 h within the Best-Track. Furthermore, the 6-h increase in TC intensity in the ERA-I for TC Flo is greater than the largest 6-h increase in Best-Track TC intensity [45 kt for EPAC TC Kiko (1983)] within any of the three basins for the period of study. The causes of these nonphysical structures are being investigated in both the CFSR (B. Kistler and D. Kleist 2011, personal communication) and the ERA-I (D. Dee 2010, personal communication). These cases illustrate that statistics based on a large composite do not tell the complete story and can hide pertinent case to case differences that would impact the calculation of quantities such as power dissipation and integrated kinetic energy (Powell and Reinhold 2007) that are dependent on TC structure.

### 4. Conclusions

The results presented in this study represent a comprehensive attempt at quantifying TC position differences and intensity among five reanalysis datasets. Within the NATL and WPAC, TC position differences are observed to decrease toward observationally dense regions within the ERA-40, ERA-I, and MERRA. The CFSR and JRA-25 exhibit much smaller position differences than the ERA-40, ERA-I, and MERRA because of the use of vortex relocation and TC wind profile retrievals, respectively. More modest relationships are found between reanalysis TC intensity and position difference in each basin. Position difference is also found to decrease with increasing Best-Track intensity in all three basins. Of the three basins studied, the EPAC is generally found to have the largest mean position differences potentially due to a relative dearth of observations, the movement of TCs away from the most observation dense portion of the basin over time, the comparatively weak intensities of reanalysis TCs, and the sharp gradient in elevation between the EPAC and Mexico.

Consistent with prior research, the coarse resolution of the reanalyses results in a gross underestimation of TC intensity relative to the Best-Track. However, that underestimation appears to be even greater than that explained solely by the coarse resolution of the datasets. Correlation coefficients between Best-Track and reanalysis TC intensity show that at most only slightly greater than half of the variance is explained. Moreover, gridded maps of correlation coefficients between Best-Track and reanalysis TC intensity are found to exhibit substantial variability in magnitude within each basin. These results imply that substantial differences occur between Best-Track and reanalysis TC intensity. Both Best-Track latitude and extended Best-Track size have comparable or stronger correlation coefficients with reanalysis intensity within the NATL and WPAC relative to the correlations in the Best-Track. Compared to the NATL and WPAC, intensity is more muted within the EPAC possibly due to the sparseness of observations, the propagation of TCs away from the most observation dense portion of the basin with time, the smaller mean size of TCs in this basin, the comparatively shorter Best-Track lifespan of EPAC TCs, and the steep elevation gradient in this basin. Of the five reanalyses, the CFSR and JRA-25 are found to have both strongest intensities, particularly for VMAX<sub>10m</sub>, and largest correlations with Best-Track intensity.

With regards to the life cycle of TC intensity, all three basins exhibit relatively weak correlations between age and intensity within the Best-Track with significant differences found in the strength of this relationship as well as the timing of peak intensity within each basin. For reanalysis TCs within the NATL and WPAC, the strength of this relationship was generally found to be stronger than the Best-Track while the EPAC typically exhibited weaker correlations. Specifically, reanalysis TCs are found to intensify too slowly prepeak intensity and reach peak intensity too late compared to their Best-Track counterparts. The combination of the large biases in reanalysis intensity together with the weaker than observed relationship between age and intensity implies that the life cycle of reanalysis TC intensity is markedly different for TCs in the EPAC compared to the NATL and WPAC.

The results presented here suggest that caution is needed regarding the use of reanalyses in studying TC intensity or position. Rather than assuming the reanalysis TC is located at the grid point closest to its Best-Track counterpart, these results indicate that the independent tracking of reanalysis TCs should be strongly considered since mean position differences can be hundreds of kilometers depending on the TC location and reanalysis used. The discrepancies in TC position and intensity with the Best-Track may also impact the fidelity of the large-scale environment on short time scales owing to the misrepresentation of feedbacks between TCs and these larger scales. Furthermore, the underestimation of both the magnitude of reanalysis TC intensity and the life cycle of reanalysis TC intensity (particularly major TCs) relative to the Best-Track suggests that the bias correction of reanalysis TC intensity would not yield an intensity distribution comparable to the Best-Track. Given that metrics such as accumulated cyclone energy (Bell and Chelliah 2006) and power dissipation used for quantifying intensity are more strongly influenced by the occurrence of intense TCs, the inability to properly capture the true variability of VMAX<sub>10m</sub> would be a significant caveat in using reanalyses for such studies.

Acknowledgments. This research was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program Grant 10-Earth10R-0036 and NSF Grant ATM-0842618. This research has benefited from critical and constructive input from Michael Bosilovich of GSFC/NASA, Daryl Kleist of EMC/NOAA, Bob Kistler of EMC/NOAA, Henry Winterbottom of ESRL/NOAA, and four anonymous reviewers. This work would not have been possible without the availability of the CFSR, ERA-40, ERA-I, and JRA-25 dataset from the respective agencies and NCAR as well as the MERRA dataset from NASA. Some of the computations were completed using GrADS, provided by COLA/IGES. All figures along with some of the computations were done in IDL, provided by ITT.

#### REFERENCES

- Andersson, E., and Coauthors, 2005: Assimilation and modeling of the atmospheric hydrological cycle in the ECMWF forecasting system. *Bull. Amer. Meteor. Soc.*, 86, 387–402.
- Bauer, P., P. Lopez, A. Benedetti, D. Salmond, and E. Moreau, 2006a: Implementation of 1D+4D-Var assimilation of precipitationaffected microwave radiances at ECMWF. I: 1D-Var. *Quart. J. Roy. Meteor. Soc.*, 132, 2277–2306.
- —, —, D. Salmond, A. Benedetti, S. Saarinen, and M. Bonazzola, 2006b: Implementation of 1D+4D-Var assimilation of precipitation-affected microwave radiances at ECMWF. II: 4D-Var. *Quart. J. Roy. Meteor. Soc.*, **132**, 2307–2332.
- Bell, G., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. J. Climate, 19, 590–612.
- Bloom, S., L. Takacs, A. da Silva, and D. Ledvina, 1996: Data assimilation using incremental analysis updates. *Mon. Wea. Rev.*, 124, 1256–1271.
- Chan, J., and R. Williams, 1987: Analytical and numerical studies of the beta effect in tropical cyclone motion. Part I: Zero mean flow. J. Atmos. Sci., 44, 1257–1265.
- Chavas, D., and K. Emanuel, 2010: A QuikSCAT climatology of tropical cyclone size. *Geophys. Res. Lett.*, 37, L18816, doi:10.1029/ 2010GL044558.
- Chu, J., C. Sampson, A. Levine, and E. Fukada, 2002: The Joint Typhoon Warning Center tropical cyclone Best-Tracks, 1945– 2000. Naval Research Laboratory Reference NRL/MR/7540-02-16, 22 pp.
- Cocks, S., and W. Gray, 2002: Variability of the outer wind profiles of western North Pacific typhoons: Classifications and techniques for analysis and forecasting. *Mon. Wea. Rev.*, **130**, 1989–2005.
- Cordeira, J., 2010: Tropical-extratropical interactions conducive to intraseasonal variability in Northern Hemisphere available potential energy. Preprints, 29th Conf. on Hurricanes and Tropical Meteorology, Tuscon, AZ, Amer. Meteor. Soc, 8D.7. [Available online at http://ams.confex.com/ams/29Hurricanes/ techprogram/paper\_168925.htm.]
- Cressman, G., 1959: An operational objective analysis system. Mon. Wea. Rev., 87, 367–374.
- Dee, D., and S. Uppala, 2009: Variational bias correction of satellite radiance data in the ERA-Interim reanalysis. *Mon. Wea. Rev.*, 135, 1830–1841.
- —, and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597.
- Demuth, J., M. DeMaria, and J. Knaff, 2009: Improvement of advanced microwave sounding unit tropical cyclone intensity and size estimation algorithms. J. Appl. Meteor. Climatol., 45, 1573–1581.
- Derber, J., and W. Wu, 1998: The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system. Mon. Wea. Rev., 126, 2287–2299.
- Dong, K., and C. Neumann, 1986: The relationship between tropical cyclone motion and environmental geostrophic flows. *Mon. Wea. Rev.*, **114**, 115–122.
- Dvorak, V., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, 420– 430.

- Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686–688.
- Evans, C., and R. Hart, 2008: Analysis of the wind field evolution associated with the extratropical transition of Bonnie (1998). *Mon. Wea. Rev.*, **136**, 2047–2065.
- Farfán, L., and J. Zehnder, 1997: Orographic influence on the synoptic-scale circulations associated with the genesis of Hurricane Guillermo (1991). *Mon. Wea. Rev.*, **125**, 2683–2698.
- Fiorino, M., and R. Elsberry, 1989: Some aspects of vortex structure related to tropical cyclone motion. J. Atmos. Sci., 46, 975–990.
- Harr, P., and J. Dea, 2009: Downstream development associated with the extratropical transition of tropical cyclones over the western North Pacific. *Mon. Wea. Rev.*, **137**, 1295–1319.
- Hart, R., 2010: An inverse relationship between aggregate Northern Hemisphere tropical cyclone activity and subsequent winter climate. *Geophys. Res. Lett.*, 38, L01705, doi:10.1029/ 2010GL045612.
- —, and J. Evans, 2001: A climatology of the extratropical transition of Atlantic tropical cyclones. J. Climate, 14, 546–564.
- —, R. Maue, and M. Watson, 2007: Estimating local memory of tropical cyclones through MPI anomaly evolution. *Mon. Wea. Rev.*, 135, 3990–4005.
- Hatsushika, H., J. Tsutsui, M. Fiorino, and K. Onogi, 2006: Impact of wind profile retrievals on the analysis of tropical cyclones in the JRA-25 reanalysis. J. Meteor. Soc. Japan, 84, 891–905.
- Hawkins, H., and D. Rubsam, 1968: Hurricane Hilda, 1964. Mon. Wea. Rev., 96, 617–636.
- Jarvinen, B., C. Neumann, and M. Davis, 1984: Tropical cyclone data tape for the North Atlantic basin, 1886–1983: Contents, limitations and uses. NOAA Tech. Memo. NWS NHC 22, 24 pp.
- Jiang, H., and E. Zipser, 2010: Contribution of tropical cyclones to the global precipitation from eight seasons of TRMM data: Regional, seasonal, and interannual variations. J. Climate, 23, 1526–1543.
- Jones, S., and Coauthors, 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Wea. Forecasting*, 18, 1052–1092.
- Kimball, S., and M. Mulekar, 2004: A 15-year climatology of North Atlantic tropical cyclones. Part I: Size parameters. J. Climate, 17, 3555–3575.
- Knaff, J., and R. Zehr, 2007: Reexamination of tropical cyclone wind-pressure relationships. *Wea. Forecasting*, 22, 71–88.
- Kossin, J., and Coauthors, 2007: Estimating hurricane wind structure in the absence of aircraft reconnaissance. *Wea. Forecasting*, **22**, 89–101.
- Landsea, C., and Coauthors, 2004: A reanalysis of hurricane andrew's intensity. *Bull. Amer. Meteor. Soc.*, **85**, 1699–1712.
  —, B. Harper, K. Hoarau, and J. Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science*, **313**, 452–453.
- Liu, Q., T. Marchok, H. Pan, M. Bender, and S. Lord, 2000: Improvements in hurricane initialization and forecasting at NCEP with global and regional (GFDL) models. NOAA Tech. Proc. Bull. 472, 7 pp.
- Maloney, E., and D. Hartmann, 2000a: Modulation of eastern North Pacific hurricanes by the Madden–Julian oscillation. *J. Climate*, **13**, 1451–1460.
  - -, and —, 2000b: Modulation of hurricane activity in the Gulf of Mexico by the Madden–Julian oscillation. *Science*, 287, 2002–2004.
- Manning, D., 2007: The utility of the ERA-40 cyclone phase space in trend diagnosis and North Atlantic tropical cyclone reanalysis.M.S. thesis, Depatment of Meteorology, The Florida State University, 79 pp.

- —, and R. Hart, 2007: Evolution of North Atlantic ERA-40 tropical cyclone representation. *Geophys. Res. Lett.*, **34**, L05705, doi:10.1029/2006GL028266.
- McTaggart-Cowan, R., L. Bosart, J. Gyakum, and E. Atallah, 2007: Hurricane Katrina (2005). Part II: Evolution and hemispheric impacts of a diabatically generated warm pool. *Mon. Wea. Rev.*, **135**, 3927–3949.
- Merrill, R., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.*, **112**, 1408–1418.
- Molinari, J., D. Vollaro, S. Skubis, and M. Dickinson, 2000: Origins and mechanisms of eastern Pacific tropical cyclogenesis: A case study. *Mon. Wea. Rev.*, **128**, 125–139.
- Mozer, J., and J. Zehnder, 1996: Lee vorticity production by largescale tropical mountain ranges. Part I: Eastern North Pacific tropical cyclogenesis. J. Atmos. Sci., 53, 521–538.
- Neumann, C., B. Jarvinen, C. McAdie, and J. Elms, 1993: Tropical cyclones of the North Atlantic Ocean, 1871–1992. Historical Climatology Series 6-2, NOAA, 193 pp.
- Onogi, K., and Coauthors, 2007: The JRA-25 Reanalysis. J. Meteor. Soc. Japan, 85, 369–432.
- Powell, M., and T. Reinhold, 2007: Tropical cyclone destructive potential by integrated kinetic energy. *Bull. Amer. Meteor. Soc.*, 88, 513–526.
- Riemer, M., S. Jones, and C. Davis, 2008: The impact of extratropical transition on the downstream flow: An idealized modelling study with a straight jet. *Quart. J. Roy. Meteor. Soc.*, 134, 69–91.
- Rienecker, M., and Coauthors, 2011: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. J. Climate, 24, 3624–3648.
- Saha, S., and Coauthors, 2010: The NCEP climate forecast system reanalysis. Bull. Amer. Meteor. Soc., 91, 1015–1057.
- Schenkel, B., and R. Hart, 2010: An examination of the spatial and temporal extent of the climate memory of tropical cyclones. Preprints, 22nd Conf. on Climate Variability and Change, Atlanta, GA, Amer. Meteor. Soc., 112. [Available online at http://ams.confex.com/ams/90annual/techprogram/paper\_163674. htm.]
- Shapiro, L., and H. Willoughby, 1982: The response of balanced hurricanes to local sources of heat and momentum. J. Atmos. Sci., 39, 378–394.
- Simmons, A., S. Uppala, D. Dee, and S. Kobayashi, 2007: ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter*, No. 110, ECMWF, Reading, United Kingdom, 25–35.
- Sriver, R., and M. Huber, 2006: Low frequency variability in globally integrated tropical cyclone power dissipation. *Geophys. Res. Lett.*, **33**, L11705, doi:10.1029/2006GL026167.
- —, and —, 2007: Observational evidence for an ocean heat pump induced by tropical cyclones. *Nature*, **447**, 577–580.
- Thépaut, J., 2006: Assimilating only surface pressure observations in 3D and 4DVAR. Proc. Workshop on Atmospheric Reanalysis, Reading, United Kingdom, ECMWF, 107–112.
- —, P. Courtier, G. Belaud, and G. Lemaître, 1996: Dynamical structure functions in a four-dimensional variational assimilation: A case study. *Quart. J. Roy. Meteor. Soc.*, **122**, 535–561.
- Thorne, P., and R. Vose, 2010: Reanalyses suitable for characterizing long-term trends. Bull. Amer. Meteor. Soc., 91, 353–361.
- Trenberth, K., and J. Fasullo, 2007: Water and energy budgets of hurricanes and implications for climate change. J. Geophys. Res., 112, D23107, doi:10.1029/2006JD008304.
- Truchelut, R., and R. Hart, 2011: Quantifying the possible existence of undocumented Atlantic warm-core cyclones in

NOAA/CIRES 20th century reanalysis data. *Geophys. Res. Lett.*, **38**, L08811, doi:10.1029/2011GL046756.

- Turk, M., D. Vollaro, and J. Molinari, 1995: Large-scale aspects of active and inactive periods of eastern Pacific tropical cyclogenesis. Preprints, 21st Conf. on Hurricanes and Tropical Meteorology, Miami, FL, Amer. Meteor. Soc., 106–107.
- Uppala, S., and Coauthors, 2004: ERA-40: ECMWF 45-year reanalysis of the global atmosphere and surface conditions 1957– 2002. ECMWF Newsletter, No. 101, ECMWF, Reading, United Kingdom, 2–21.
- —, and Coauthors, 2005: The ERA-40 Re-Analysis. *Quart. J. Roy. Meteor. Soc.*, **131**, 2961–3012.
- Vecchi, G., and T. Knutson, 2008: On estimates of historical North Atlantic tropical cyclone activity. J. Climate, 21, 3580–3600.
- Velden, C., 1993: The relationship between tropical cyclone motion, intensity, and the vertical extent of the environmental steering layer in the Atlantic basin. Preprints, 20th Conf. on Hurricanes and Tropical Meteorology, San Antonio, TX, Amer. Meteor. Soc., 31–34.

- Walsh, K., M. Fiorino, C. Landsea, and K. McInnes, 2007: Objectively determined resolution-dependent threshold criteria for the detection of tropical cyclones in climate models and reanalyses. J. Climate, 20, 2307–2314.
- Weatherford, C., and W. Gray, 1988: Typhoon structure as revealed by aircraft reconnaissance. Part II: Structural variability. *Mon. Wea. Rev.*, **116**, 1044–1056.
- Whitaker, J., G. Compo, and J. Thépaut, 2009: A comparison of variational and ensemble-based data assimilation systems for reanalysis of sparse observations. *Mon. Wea. Rev.*, 137, 1991–1999.
- Zehnder, J., 1991: The interaction of planetary-scale tropical easterly waves with topography: A mechanism for the initiation of tropical cyclones. J. Atmos. Sci., 48, 1217–1230.
- —, 1993: The influence of large-scale topography on barotropic vortex motion. J. Atmos. Sci., **50**, 2519–2532.
- —, D. Powell, and D. Ropp, 1999: The interaction of easterly waves, orography, and the intertropical convergence zone in the genesis of eastern Pacific tropical cyclones. *Mon. Wea. Rev.*, **127**, 1566–1585.